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MILLIMETER WAVE SATELLITE CONCEPTS

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L. D. Holland, Associate Project Director
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GEORGIA INSTITUTE OF TECHNOLOGY

Engineering Experiment Station

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center
Contract NAS3–20110

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VOLUME II

TECHNICAL REPORT

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FOREWORD

The "Millimeter Wave Satellite Concepts" project under Contract NAS3-20110 was conducted by the Engineering Experiment Station (EES) at Georgia Tech. The program was administered under Georgia Tech Project A-1855 by the Systems Technology Branch of the Systems Engineering Division.

This report describes a portion of the work performed during the period June 1976 through June 1978. The bulk of this effort is reported in Volume I. The program was managed by the NASA/Lewis Research Center Space Flight Systems Study Office. The NASA Program Manager was Mr. Grady Stevens.

The Georgia Tech Project Director was Dr. Neil B. Hilsen, Head of the Systems Technology Branch, with Mr. Larry D. Holland serving as Associate Project Director. The project was conducted under the general supervision of Mr. Robert P. Zimmer, Chief of the Systems Engineering Division. In addition to the project director and associate project director, the project team was comprised of the key personnel from the EES listed below along with their principal area of contribution.

R. W. Wallace	Communication Systems/Applications
D. L. Kelly	Annual Cost Formulation
R. E. Thomas	Systems Integration/Switching Technology
F. H. Vogler	Communications Systems/Systems Analysis

SUMMARY

This research program addressed the identification of technologies necessary for development of millimeter spectrum communication satellites from a systems point of view. The objectives of the program were (1) development of a methodology for identification of potential future NASA millimeter research and development programs, and (2) testing of this methodology with selected user applications and services. The scope of the program included the entire communications network, both ground and space subsystems. The bulk of the report is in Volume I and includes (1) cost, weight, and performance models for the subsystems, (2) conceptual design for point-to-point and broadcast communications satellites, (3) analytic relationships between subsystem parameters and an overall link performance, (4) baseline conceptual systems, (5) sensitivity studies, (6) model adjustment analyses, (7) identification of critical technologies and their risks, and (8) brief R&D program scenarios for the technologies judged to be moderate or extensive risks. Subsystem models used in the study are applicable over a frequency range from about 18 GHz to 80 GHz, but the primary emphasis in the study has been for 40 and 50 GHz.

Volume I provides system costs expressed as total capital cost; this volume provides costs from commercial viewpoint in terms of annual cost per cnannel to the user.

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SECTION 1

INTRODUCTION

The overall objectives of this study have been to identify the technologies necessary to satisfy communication services in the millimeter wave region, and to assess the relative risks of these technologies. Specifically, these were to (1) develop a methodology for identifying viable and appropriate technologies for future NASA millimeter research and development programs, and (2) test this methodology with selected user applications and services. The Volume I Technical Report, entitled Millimeter Wave Satellite Concepts [1], documents the major portion of this work. It describes the models developed to estimate subsystem costs and weights, conceptual designs for point-to-point and broadcast communication applications, an optimization methodology for design tradeoff studies, an identification of critical technologies and their risks, and conclusions and recommendations for dealing with high risk technologies.

The Volume II Technical Report presents an extension of the work described in Volume I. This report describes (1) the modifications made to the conceptual design applications, (2) the additional models generated for annual cost calculations, and (3) the resulting estimated annual costs for the modified concepts. In reading this report, it will be helpful to have the Volume I Technical Report available for reference.

The modified communication satellite system concept utilizes the same ground and space subsystem models, but the design is reoptimized for a system of three satellites (one active and one inactive satellite in orbit and one spare satellite on the ground) with the same number of ground stations as treated previously. Since the optimal design criteria is minimum total system cost (space segment and ground stations), the change from one to three satellites resulted in a new system design with increased performance requirements (and cost) for the ground systems.

Also in this report, the communication system costs have been re-expressed as "annual costs per channel to the user." That is, the capital costs have been combined with the operating costs, return on the investment to the operator, taxes, etc., and have been amortized over a reasonable financial horizon to estimate an equivalent annual cost for the system. This annual cost was then divided by the predicted channel capacity of the satellite system to produce the estimated annual cost per channel to the user.

The approach utilized in this modification has been to: (1) develop annual costs and channel capacity models; (2) incorporate these models into the existing computerized Satellite Cost Optimization Routine (SCOR); (3) repeat the optimal design computer runs only for the nominal cases of the point-to-point and broadcast applications; and (4) estimate the annual cost per channel to the user for the non-nominal cases. This last item is accomplished by scaling the Volume I results for capital cost per single satellite to annual cost per multiple satellite by a nominal case scale factor for the appropriate application. The validity of the scaling approach for the non-nominal cases (i.e. different link reliabilities) is based upon the linear relationship between capital cost and annual cost.

Section 2 of this report describes briefly the annual cost model and channel capacity relationships which are described more fully in Appendices I and II, respectively. Section 3 presents the results of this modified task in terms of both the reoptimized nominal cases and the scaled result for non-nominal cases. The point-to-point application results are presented for both 40/50 GHz and the 18/30 GHz cases; the broadcast application results are for 40/50 GHz. Section 4 presents the conclusions drawn from the task modification.

SECTION 2

ANNUAL COST AND CHANNEL CAPACITY MODELS

The Satellite Cost Optimization Routine (SCOR) developed and described in the Volume I Report employs cost and performance models for satellite communication subsystems and numerical optimization routines to determine the satellite link design which will provide the specified carrier-to-noise ratio for a minimum total capital cost. This section describes models for annual cost and channel capacity which have since been incorporated into SCOR in response to a study task modification. The computer program calculates and displays both the capital costs and the "annual cost per channel to the ultimate user" for the optimized communication system. Appendices I and II contain derivations of the annual cost model and the channel capacity models, respectively. The following paragraphs utilize results from the Appendices and indicate how the models are used within SCOR to provide additional insight into the economic viability of the Millimeter Wave Satellite Concepts.

The annual cost model takes into account the capital investment for the satellite and ground systems, anticipated lifetimes of the satellite and the ground systems, and such financial parameters as the length of the financial planning horizon, the allowable return on investment in the regulated industry, the income tax rate applicable to the corporate venture, and an annual rate of escalation for operation and maintenance costs. Property taxes, fire insurance premiums, and ground system operation and maintenance costs are also included. The initial capital investment includes not only the satellites and the communication ground stations, but also the tracking telemetry, and control ground stations. The expression of annual cost of the system is a function of these parameters and takes into account the times at which the costs and revenues occur utilizing the concept of net present value. This uses a discount rate consistent with the rate of return allowed by the regulatory agency. The model for the equivalent annual cost of the total satellite communications system is derived in Appendix I and is summarized here. The annual charge for the complete set of communication channels is related to the present value of the total allowable revenues by the following:

$$\text{Annual Cost} = \frac{k}{1 - 1/(1+k)^H} \cdot PV\,(Rev_t)$$

where k is the allowable rate of return and H is the length of the planning horizon. It is worth noting that the discounted annual cost is significantly greater than just the total revenue divided by the duration, H. For a typical case of 10% rate of return and an 8-year operation period, the annual cost is 50% greater than revenue divided by eight years.

The above expression represents the annual charge for the entire communication system. The equivalent annual cost per channel to the user is determined by dividing that total annual cost by the effective number of channels; i.e., by the product of the number of simplex channels available and the utilization factor. Appendix II presents a procedure for estimating the channel capacity of the millimeter wave concepts considered during this program. Since channel capacity is a somewhat complex function of modulation, multiple-access technique, power levels, bandwidth, etc., the selected approach has been to start with results computed by COMSAT Corporation for INTELSAT IV and to denormalize those results to predict channel capacity for the millimeter concepts. The resulting channel capacity for the six transponders in the Application I concept (point-to-point communications) is 66,300 simplex voice channels or 33,150 full duplex voice channels for frequency division multiplex (FDM). Similarly, the channel capacity for time division multiplex (TDM) in Application I is 123,672 simplex channels or 61,836 full duplex channels. Similar results are also given for Application II (broadcast mode) in Appendix II.

The annual cost calculation models are implemented within SCOR at a point which follows the optimization technique to minimize unnecessary computer time requirements. The interrelation of the annual cost model with the remainder of SCOR is shown in Figure 2.1. For those scenarios in which capital investments are made at different times throughout the financial planning horizon rather than just on initial investment, it would be necessary to locate the annual cost model inside the optimization loop in order to properly account for discounting of funds.

Variation in the annual cost to the user for each simplex channel can be parameterized with respect to utilization rate after the annual cost has been calculated for 100% utilization. The actual cost per channel is given by the fully-utilized rate per channel divided by the ratio of the leased channels to the total available channels. In this analysis no consideration has been made for primary and secondary channels with different charges for guaranteed channel availability.

The models described in this section have been incorporated into SCOR, and two demonstration optimization runs have been made. The optimization runs are

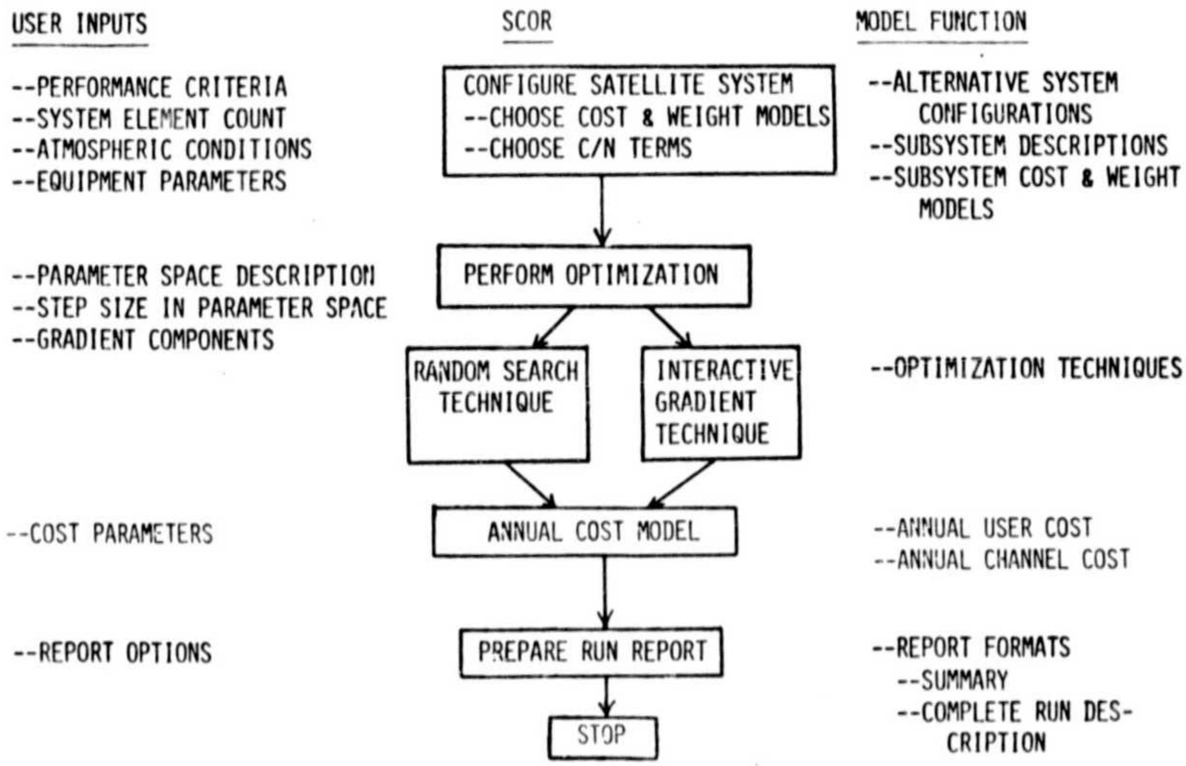

FIGURE 2.1 BLOCK DIAGRAM OF THE SATELLITE COST OPTIMIZATION ROUTINE (SCOR)

for Applications I and II and differ from the optimizations made earlier in the study by the inclusion of two communication satellites in orbit and one spare on the ground.

SECTION 3

APPLICATION RESULTS

This section presents the results of the application of the revised program SCOR to the nominal cases for point-to-point communications and broadcast communications. The resulting annual cost per channel data is used in conjunction with previous results from Volume I to produce estimated annual costs per channel variation as a function of number of ground terminals and the required link reliability.

3.1 Application I: Point-to-Point

3.1.1. System Description

A baseline conceptual system was developed for the point-to-point application from considerations presented in Section 5.2 of Volume I and from optimization analysis on the use of radomes and the choice of diversity type. The resultant system uses six ground stations, each with single station diversity for both receive and transmit. No radomes are used. The satellite, with onboard switching, is depicted in Figure 4.5 of Volume I. For baseline analysis all signal processing is assumed to be by frequency-division multiplex.

As for all analyses performed to calculate system cost, the cost for the baseline system was minimized under carrier-to-noise and weight constraints by the computer program SCOR. A complete set of the parameters required for input to this minimization is given in Table 3.1. Included are system constraints, system configuration parameters, and various assumed constants. The lower portion of Table 6.1 of Volume I gives the assumed subsystem redundancies where the constant is a multiplier on the number of subsystems operating in the baseline system.

3.1.2 Optimum Baseline System (40/50 GHz)

Figure 3.1 presents the basic output data from SCOR for the baseline case. This is analogous to Figure 6.1 of Volume I, but is for the three-satellite system and contains annual cost data in addition to capital costs. Note that the $112.7 M capital cost translates to an annual system cost of $31.8 M and a per simplex voice channel annual cost of $959 (for 50% utilization).

TABLE 3.1 POINT-TO-POINT APPLICATION BASELINE PARAMETERS

PARAMETERS	VALUE
Carrier/Noise Constraint Limit (DB)	15.00
Weight Constraint Limit (LBS)	5000
Downlink Frequency (GHZ)	40.50
Uplink Frequency (GHZ)	50.50
Satellite Channel Bandwidth (MHZ)	1000.
Number of Channels (Beams)	6
Number of Positions Per Beam	1
Reliability (Percent)	99.90
Rain Rate (MM/HR)	50.00
Number of TV Headins	12
Number of Voice Multiplexes	12
Digital Data Rate (MBS)	3.000
Bulk Data Rate (MBS)	200.0
Bulk Data Volume (MB)	1000.
Number of Ground Stations	6
Ground Transmitters Per Link	6
Ground Receivers Per Link	2
Channel Capacity	66,300
Number of Subchannels Per Channel	5
Ground Station Bandwidth (MHZ)	1000.
Diversity Link Receive Cost (K$/MI)	100.7
Diversity Link Transmit Cost (K$/MI)	40.30
Diversity Link Range (MI)	9.940
Ground Station Building Cost (K$)	100.0
Diversity Station Building Cost (K$)	50.00
Marginal Income Tax Rate	0.48
Rate of Return on Investment	0.13
Financial Planning Horizon (Years)	8
Life of Satellite (Years)	8
Life of Ground System (YEARS)	14
Tax Constant	0.015
Insurance Constant	0.012
Cost of Debt	0.085
Ratio of Debt to Total Capitalization	0.45
Fraction of Channel Sellable	0.50
Average Growth of Operating Costs	0.065
Satellite Operating Cost Constant	0.01
Ground System Operating Cost Constant	0.04
Launch Cost (K$/LB)	5.0
Launch Insurance Rate	0.1
Number of Satellites Purchased	3
Number of Launches	2
Uplink Misc. Losses (DB)	7.000
Downlink Misc. Losses (DB)	8.000
Atmosphere Temperature (K)	300.0

SATELLITE COST OPTIMIZATION ROUTINE (SCOR)   ENGINEERING EXPERIMENT STATION   GEORGIA INSTITUTE OF TECHNOLOGY

RUN10A

OPTIMUM SYSTEM DESIGN

***** OPTIMAL VARIABLES

VARIABLE	MIN	MAX	OPT
GROUND XMIT POWER (WATTS)	2357.	2417.	2390.
GROUND ANTENNA DIAMETER (M)	8.006	8.042	8.025
GROUND REC NOISE FIGURE (LIN)	1.200	1.372	1.210
SATELLITE XMIT POWER (WATTS)	11.39	258.9	128.9
SATELLITE REC NOISE FIGURE (LIN)	3.323	3.511	3.351
SATELLITE ANTENNA SIZE (M)	2.554	2.573	2.562
GROUND ANT. POINTING ERROR (DEG)	.2031E-01	.2211E-01	.2116E-01
ATTITUDE CONTROL ERROR (DEG)	.2685E-01	.3003E-01	.2691E-01
STATION KEEPING ACCURACY	.3113E-02	.6609E-02	.4019E-02
LOG PR(FAIL DL)/PR(FAIL UL)	-.9821E-01	-.9431E-01	-.9816E-01

***** COMMUNICATION SYSTEM PARAMETERS

CARRIER/NOISE (DB)	15.1
UPLINK RAIN ATTN (DB)	21.7
DOWNLINK RAIN ATTN (DB)	18.3
G/T (DB/K)	50.2
ERP (DB)	103.7

*****GROUND SUBSYSTEMS

QUANTITY	SUBSYSTEM	COST(K$)	% OF TOTAL
12	GROUND ANTENNA	9564.734	8.5
0	RADOME	0.000	0.0
12	GROUND POINTING AND CONTROL	4581.580	4.1
24	GROUND TRANSMITTER	5298.555	4.7
24	GROUND RECEIVER	1714.418	1.5
12	GROUND SIGNAL PROCESSING	3340.450	3.0
6	BULK DATA STORAGE	4050.000	3.6
6	HIGH SPEED MODEM	312.000	.3
6	TELEVISION HEADIN	2220.000	2.0
6	VOICE MULTIPLEX	1860.000	1.7
6	DIVERSITY LAND LINE RECEIVE	6005.748	5.3
6	DIVERSTY LAND LINE TRANSMIT	2403.492	2.1
6	GROUND STATION BUILDING	600.000	.5
6	DIVERSITY STATION BUILDING	300.000	.3
1	GROUND T,T&C	3861.813	3.4
		----------	-------
		46112.789	40.9

FIGURE 3.1 POINT-TO-POINT APPLICATION, 40/50 GHz
OPTIMUM BASELINE SYSTEM

***** SPACE SUBSYSTEMS

QUANTITY	SUBSYSTEM	----TOTAL SPACE SYSTEM---- 3 SATELLITES / 2 LAUNCHES COST(K$)	% OF TOTAL	-----------PER SATELLITE----------- COST(K$)	WEIGHT(LBS)	WEIGHT(%)
6	SATELLITE ANTENNA	12190.462	10.8	4063.487	129.0	6.0
36	SATELLITE TRANSMITTER	3791.439	3.4	1263.813	267.1	12.5
36	SATELLITE RECEIVER	1656.000	1.5	552.000	120.0	5.6
270	SPACE SIGNAL PROCESSING (SWITCHES)	904.500	.8	301.500	174.6	8.2
135	SPACE SIGNAL PROCESSING (FILTERS)	189.000	.2	63.000	49.6	2.3
27	SPACE SIGNAL PROCESSING (COMBINERS)	54.000	.0	18.000	10.8	.5
3	ATTITUDE CONTROL SYSTEM	5037.063	4.5	1679.021	76.0	3.6
3	STATION KEEPING SYSTEM	8858.088	7.9	2952.696	345.6	16.2
3	STRUCTURE AND THERMAL CONTROL	5985.381	5.3	1995.127	514.3	24.1
3	SATELLITE POWER SUPPLY	1718.041	1.5	572.680	448.1	21.0
2	LAUNCH COST	21350.007	18.9	10675.004	0.0	0.0
2	LAUNCH INSURANCE	4827.266	4.3	2413.633	0.0	0.0
		----------	-------	----------	--------	-----
		66561.247	59.1	26549.961	2135.0	100.0

SYSTEM OPTIMIZATION FOR TWO SATELLITES IN ORBIT AND ONE SPARE
ON THE GROUND WITH LAUNCH AND T,T&C COSTS INCLUDED

TOTAL SYSTEM CAPITAL COST	(K$)	112674.036
ANNUAL SYSTEM COST	(K$)	31755.286
VOICE CHANNEL COST	($/CHANNEL)	959.

***** FINANCIAL VARIATIONS

	VALUE	ANNUAL SYSTEM COST (K$)	VOICE CHANNEL COST($/CHANNEL)
RATE OF RETURN ON INVESTMENT	.110	28687.183	866.
RATE OF RETURN ON INVESTMENT	.150	34894.411	1054.
FINANCIAL PLANNING HORIZON (YEARS)	4.000	35811.433	1081.
FINANCIAL PLANNING HORIZON (YEARS)	8.000	31755.286	959.
LIFE OF SATELLITE (YEARS)	8.000	31755.286	959.
LIFE OF SATELLITE (YEARS)	10.000	31484.261	951.
LIFE OF GROUND SYSTEM (YEARS)	10.000	31969.872	965.
LIFE OF GROUND SYSTEM (YEARS)	16.000	31688.228	957.
COST OF DEBT	.080	32019.723	967.
COST OF DEBT	.110	30433.099	919.
RATIO OF DEBT TO TOTAL CAPITALIZATION	.300	33253.764	1004.
RATIO OF DEBT TO TOTAL CAPITALIZATION	.600	30256.808	913.
AVERAGE GROWTH OF OPERATING COSTS	.048	31413.796	950.
AVERAGE GROWTH OF OPERATING COSTS	.090	32134.186	970.

FIGURE 3.1 POINT-TO-POINT APPLICATION, 40/50 GHz OPTIMUM BASELINE SYSTEM, (CONTINUED)

3.1.3 Extension to Non-Baseline System

Figure 6.2 of Volume I shows the variation in cost per terminal as a function of required link reliability (rain attenuation factor only). By assuming that annual cost per channel is linearly related to capital cost, one can use the results of the SCOR run of Table 3.1 to "Scale" Figures 6.2 and 6.3 of Volume I to generate plots of annual cost per channel as a function of link reliability or of the number of terminals as in Figures 3.2 and 3.3 below. Note in Figure 3.2 that as reliability increases from 90% to 99.9%, the annual cost per simplex voice channel increases from $775 to $959 (for 50% utilization).

The number of ground stations was varied from 2 to 10 in Volume I to examine the effect of this change on per terminal cost. This was done for both FDM and TDM signal processing to determine changes in the relative attractiveness of these two techniques. The results, after scaling, are replotted as Figure 3.3. The increasing cost for FDM as a function of the number of terminals and the generally lower cost for TDM than FDM are both due to the fact that FDM channel capacity decreases much more rapidly than TDM channel capacity as more terminals are added to the system (refer to Appendix II).

3.1.4 Extension to 18/30 GHz

Figures 6.5 and 6.6 in Volume I are plots of capital cost per terminal vs. reliability and number of terminals for 18/30 GHz links. These plots have been "scaled" by the factor used above with 40/50 GHz to generate the plots of annual cost per voice channel vs. link reliability and number of terminals as presented below as Figures 3.4 and 3.5, respectively.

3.2 Application II: Broadcast

3.2.1. System Description

The objective of the initial broadcast application concept in Volume I was to provide total U.S. coverage using adjacent spot beams with 99.5% link reliability (rain considerations only) for wideband uses such as video distribution. Preliminary power calculations indicated that very large (heavy) satellites would be required for this concept, and a compromise baseline design with limited simultaneous beam utilization and with on-board switching was developed. This design provides up to 96.5% link reliability with the assumed subsystem constraints (e.g., satellite weight). However, a baseline design with 95% reliability was used to facilitate the sensitivity analysis. Other system configurations such as multiple satellites or a very large satellite could possibly achieve the desired 99.5% reliability; this is a subject for future investigation.

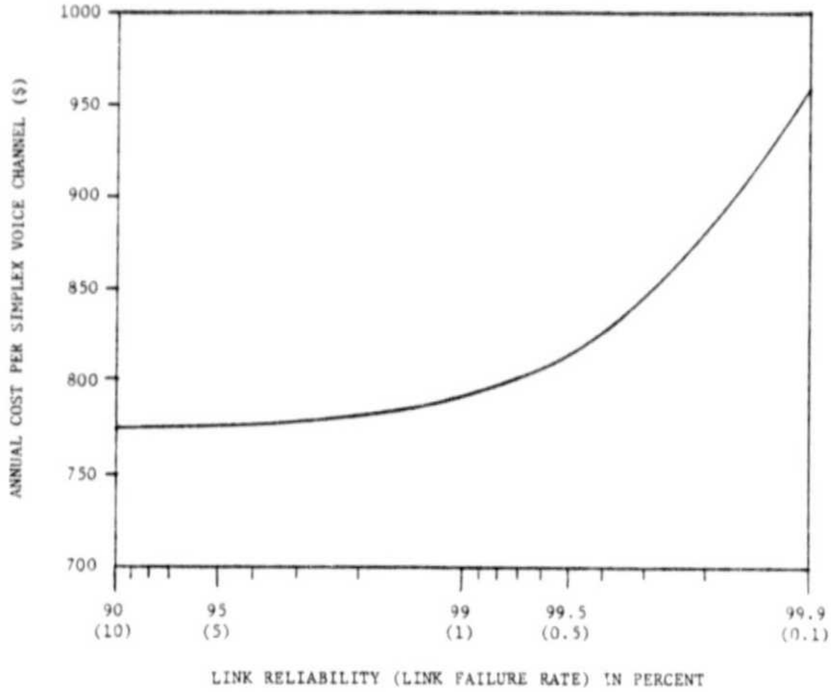

FIGURE 3.2 ANNUAL COST PER CHANNEL VERSUS LINK RELIABILITY FOR POINT-POINT SERVICE AT 40/50 GHz (50% UTILIZATION).

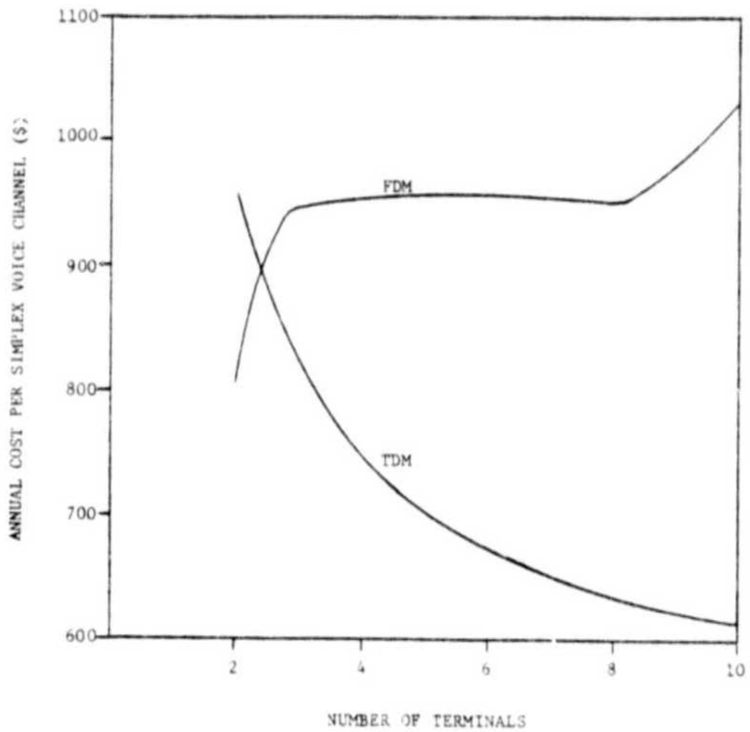

FIGURE 3.3 ANNUAL COST PER CHANNEL VERSUS NUMBER OF TERMINALS - FDM AND TDM FIXED POINT-POINT SYSTEM AT 40/50 GHz FOR 99.9% RELIABILITY (50% UTILIZATION).

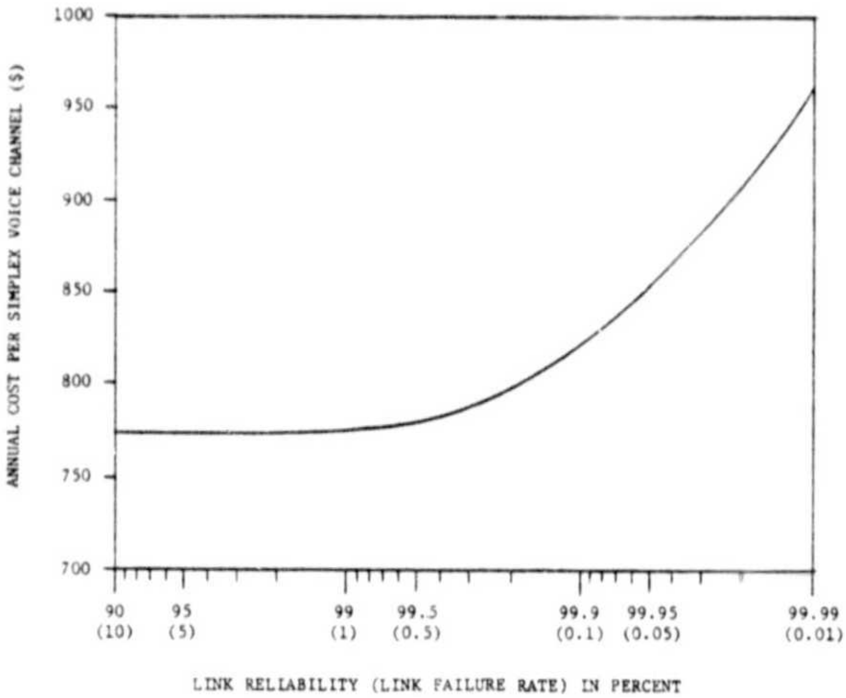

FIGURE 3.4 ANNUAL COST PER CHANNEL VERSUS RELIABILITY FOR POINT-TO-POINT SERVICE AT 18/30 GHz (50% UTILIZATION).

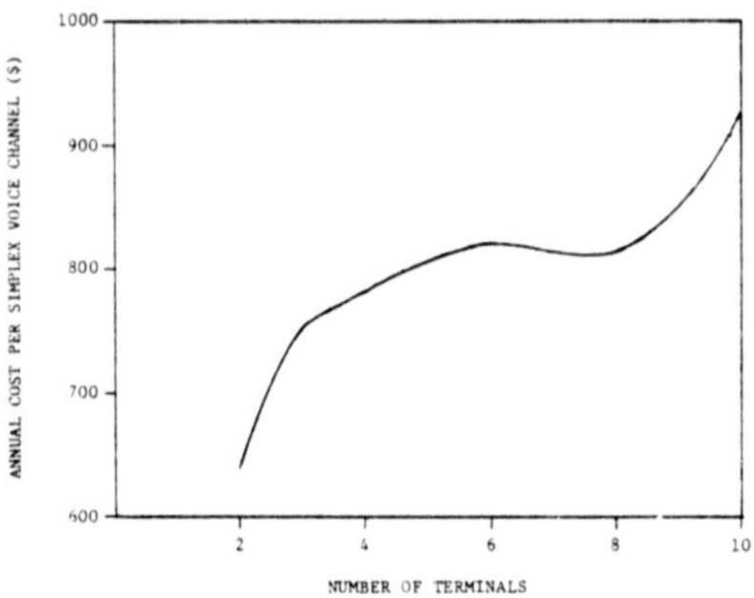

FIGURE 3.5 ANNUAL COST PER CHANNEL VERSUS NUMBER OF TERMINALS - FDM FIXED POINT-POINT SYSTEM AT 18/30 GHz FOR 99.9% RELIABILITY (50% UTILIZATION).

The weight of the on-board switches is the limiting criteria in performance of the baseline system. The resulting "broadcast" link is estimated to be able to maintain its design value carrier-to-noise ratio (12dB) 95% of the time for the assumed rain attenuation statistics. Such a communication satellite system would not be commercially marketable in the sense of current communication satellites (e.g., video entertainment); however, there may well exist suitable applications such as high volume data transfer where the time of day for the data transfer is not critical. For example, the system being planned by Satellite Business Systems (SBS) is anticipated to accomplish data transfer using a satellite link with a bit error rate of 10^{-6} with 95% reliability [2] .

3.2.2 Optimum Baseline System (40/50 GHz).

In order to achieve coverage of the entire continental United States, provisions were made for each of 6 channels to select from among 10 separate ground spot beams. To achieve the proper beam size, the satellite antenna diameter was fixed at 0.6 meter rather than used as an optimization variable. For the required coverage, 60 spots with diameter 450 KM are required. Once six receive beams and 6 transmit beams are selected, each beam carries 20 subchannels which are switched on-board the satellite. Any subchannel of a received beam may be transmitted on the corresponding subchannel of any transmitted beam. A block diagram of the satellite system is given in Figure 5.11 of Volume I. A complete tabulation of the baseline parameters is given in Table 3.2. A listing of the baseline optimization run is given in Figure 3.6.

3.2.3 Baseline Analyses

Figure 3.7 gives a plot of the sensitivity of annual cost per wideband channel to changes in required system reliability. Reliabilities higher than 96.5% were not possible under the system constraints without the use of diversity stations. Note that there is approximately a 15% increase in cost per channel as the reliability increases from 90% to 96.5%. Also, the plot is linear due to data points generated at only 90%, 95%, and 96.5% link reliability.

In order to examine the cost per terminal for various numbers of ground terminals and for various communication capabilities, channel availability was defined as the ratio of the total number of channels to the number of ground terminals. Figure 3.8 gives annual cost per wideband terminal versus availability for 120, 360 and 1080 ground stations due to absolute launch weight limits.

TABLE 3.2 BROADCAST APPLICATION BASELINE PARAMETERS

PARAMETER	VALUE
Carrier/Noise Constraint Limit (DB)	12.00
Weight Constraint Limit (LBS)	6500
Downlink Frequency (GHZ)	40.50
Uplink Frequency (GHZ)	50.50
Satellite Channel Bandwidth (MHZ)	1000.
Number of Channels (Beams)	6
Number of Positions Per Beam	10
Reliability (Percent)	95.00
Rain Rate (MM/HR)	50.00
Number of TV Headins	2
Number of Voice Multiplexes	0
Digital Data Rate (MBS	0
Bulk Data Rate (MBS)	0
Bulk Data Volume (MB)	0
Number of Ground Stations	360
Ground Transmitters Per link	1
Ground Receivers Per Link	1
Number of Subchannels Per Channel	20
Ground Station Bandwidth (MHZ)	100.0
Ground Station Building Cost (K$)	100.0
Marginal Income Tax Rate	.48
Rate of Return on Investment	.13
Financial Planning Horizon (Years)	8
Life of Satellite (Years)	8
Life of Ground System (Years)	14
Tax Constant	.015
Insurance Constant	.012
Cost of Debt	.085
Ratio of Debt to Total Capitalization	.45
Fraction of Channels Sellable	.50
Average Growth of Operating Costs	.065
Satellite Operating Cost Constant	.010
Ground Sytem Operating Cost Constant	.040
Launch Cost (K$/LB)	5
Launch Insurance Rate	.1
Number of Satellites Purchased	3
Number of Launches	2
Uplink Misc. Losses (DB)	7.000
Downlink Misc. Losses (DB)	8.000
Atomosphere Temperature (K)	300.0

SATELLITE COST OPTIMIZATION ROUTINE (SCOR)   ENGINEERING EXPERIMENT STATION   GEORGIA INSTITUTE OF TECHNOLOGY

RUNTEST

OPTIMUM SYSTEM DESIGN

***** OPTIMAL VARIABLES

VARIABLE	MIN	MAX	OPT
GROUND XMIT POWER (WATTS)	187.3	296.6	195.4
GROUND ANTENNA DIAMETER (M)	3.714	3.855	3.723
GROUND REC NOISE FIGURE (LIN)	1.811	2.961	1.948
SATELLITE XMIT POWER (WATTS)	24.72	33.28	33.03
SATELLITE REC NOISE FIGURE (LIN)	4.062	4.155	4.145
SATELLITE ANTENNA SIZE (M)	.8205	.9382	.8898
GROUND ANT. POINTING ERROR (DEG)	.2866E-01	.2953E-01	.2878E-01
ATTITUDE CONTROL ERROR (DEG)	.1970E-01	.2078E-01	.2018E-01
STATION KEEPING ACCURACY	.1908E-01	.2219E-01	.2130E-01
LOG PR(FAIL DL)/PR(FAIL UL)	.2881	.2959	.2941

***** COMMUNICATION SYSTEM PARAMETERS

CARRIER/NOISE (DB)	12.1
UPLINK RAIN ATTN (DB)	3.7
DOWNLINK RAIN ATTN (DB)	-5.0
G/T (DB/K)	37.0
ERP (DB)	86.2

*****GROUND SUBSYSTEMS

QUANTITY	SUBSYSTEM	COST(K$)	% OF TOTAL
360	GROUND ANTENNA	11531.882	4.1
0	RADOME	0.000	0.0
360	GROUND POINTING AND CONTROL	7314.455	2.6
720	GROUND TRANSMITTER	14025.793	5.0
720	GROUND RECEIVER	11421.428	4.1
720	GROUND SIGNAL PROCESSING	17749.210	6.4
0	BULK DATA STORAGE	0.000	0.0
0	HIGH SPEED MODEM	0.000	0.0
360	TELEVISION HEADIN	25200.000	9.0
0	VOICE MULTIPLEX	0.000	0.0
0	DIVERSITY LAND LINE RECEIVE	0.000	0.0
0	DIVERSTY LAND LINE TRANSMIT	0.000	0.0
360	GROUND STATION BUILDING	36000.000	12.9
0	DIVERSITY STATION BUILDING	0.000	0.0
1	GROUND T,T&C	8913.457	3.2
		----------	-------
		132156.224	47.4

FIGURE 3.6 BROADCAST APPLICATION 40/50 GHz OPTIMJM BASELINE SYSTEM

***** SPACE SUBSYSTEMS

QUANTITY	SUBSYSTEM	----TOTAL SPACE SYSTEM---- 3 SATELLITES / 2 LAUNCHES		-----------PER SATELLITE-----------		
		COST(K$)	% OF TOTAL	COST(K$)	WEIGHT(LBS)	WEIGHT(%)
6	SATELLITE ANTENNA	13594.039	4.9	4531.346	134.1	2.1
36	SATELLITE TRANSMITTER	1962.124	.7	654.041	260.8	4.2
36	SATELLITE RECEIVER	1656.000	.6	552.000	120.0	1.9
1080	SPACE SIGNAL PROCESSING (SWITCHES)	14148.000	5.1	4716.000	2603.2	41.4
540	SPACE SIGNAL PROCESSING (FILTERS)	540.000	.2	180.000	198.4	3.2
27	SPACE SIGNAL PROCESSING (COMBINERS)	256.500	.1	85.500	51.3	.8
3	ATTITUDE CONTROL SYSTEM	10809.634	3.9	3603.211	234.8	3.7
3	STATION KEEPING SYSTEM	17053.820	6.1	5684.607	880.6	14.0
3	STRUCTURE AND THERMAL CONTROL	11914.397	4.3	3971.466	1617.1	25.7
3	SATELLITE POWER SUPPLY	927.784	.3	309.261	184.0	2.9
2	LAUNCH COST	62843.345	22.5	31421.672	0.0	0.0
2	LAUNCH INSURANCE	11141.821	4.0	5570.910	0.0	0.0
		----------	-------	----------	--------	-----
		146847.463	52.6	61280.015	6284.3	100.0

SYSTEM OPTIMIZATION FOR TWO SATELLITES IN ORBIT AND ONE SPARE
ON THE GROUND WITH LAUNCH AND T,T&C COSTS INCLUDED

TOTAL SYSTEM CAPITAL COST	(K$)	279003.687
ANNUAL SYSTEM COST	(K$)	79504.558
Voice (duplex) Channel cost	($/CHANNEL)	3118.

***** FINANCIAL VARIATIONS

	VALUE	ANNUAL SYSTEM COST (K$)	VIDEO CHANNEL COST($/CHANNEL)
RATE OF RETURN ON INVESTMENT	.110	71787.898	2815.
RATE OF RETURN ON INVESTMENT	.150	87391.187	3427.
FINANCIAL PLANNING HORIZON (YEARS)	4.000	89105.284	3494.
FINANCIAL PLANNING HORIZON (YEARS)	8.000	79504.558	3118.
LIFE OF SATELLITE (YEARS)	8.000	79504.558	3118.
LIFE OF SATELLITE (YEARS)	10.000	78906.622	3094.
LIFE OF GROUND SYSTEM (YEARS)	10.000	80119.548	3142.
LIFE OF GROUND SYSTEM (YEARS)	16.000	79312.374	3110.
COST OF DEBT	.080	80159.358	3144.
COST OF DEBT	.110	76230.557	2989.
RATIO OF DEBT TO TOTAL CAPITALIZATION	.300	83215.093	3263.
RATIO OF DEBT TO TOTAL CAPITALIZATION	.600	75794.024	2972.
AVERAGE GROWTH OF OPERATING COSTS	.040	78585.612	3082.
AVERAGE GROWTH OF OPERATING COSTS	.090	80524.176	3158.

FIGURE 3.6 BROADCAST APPLICATION 40/50 GHz OPTIMUM BASELINE SYSTEM , (CONTINUED)

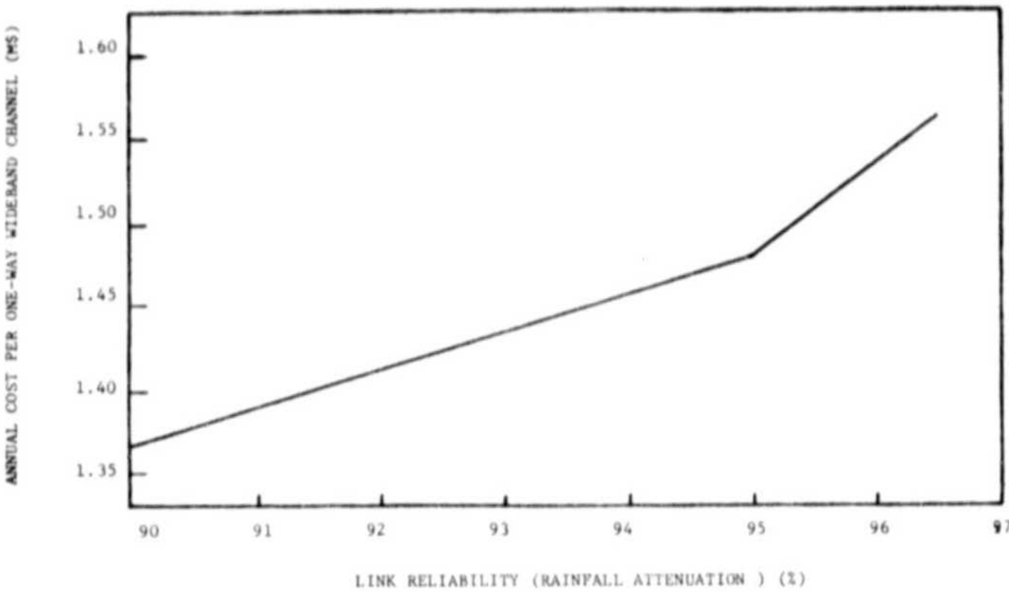

FIGURE 3.7 ANNUAL COST PER WIDEBAND CHANNEL VERSUS LINK RELIABILITY

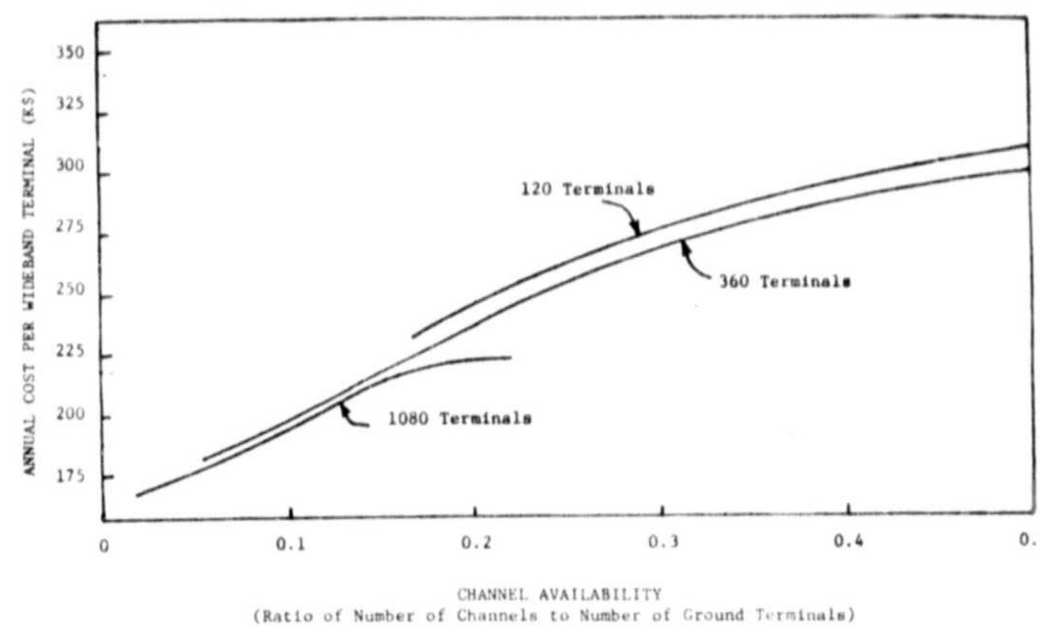

FIGURE 3.8 ANNUAL COST PER WIDEBAND TERMINAL VERSUS CHANNEL AVAILABILITY FOR 95% RELIABILITY

The increase in cost per terminal is approximately linear with increases in utilization for all numbers of ground stations. The increase is due to the cost of additional switching components and the effects of increased satellite weight on satellite operational systems and launch weight.

For a constant utilization the cost may be studied for various numbers of terminals. For the increase to 360 from 120 ground stations the drop in per terminal cost is a result of the further division of satellite cost. For the increase to 1080 ground stations, the decrease is less than would be expected due to substantially increased launch cost for the heavier satellite.

SECTION 4
CONCLUSIONS

This modification to the "Millimeter Wave Satellite Concepts" study involves a re-evaluation of the concepts developed in Volume I in terms of establishing annual user costs from a commercial viewpoint. This allows for a more direct comparison with current tariffs.

For the trunking application, typical annual cost to the user for a simplex voice channel via a high capacity 40/50 GHz satellite is approximately $950. However, the rain margin assumed is sufficient only to support 99.9% availability with respect to rain attenuation. Cases having higher reliability, such as 99.99%, were not evaluated due to excessive system costs and/or excessive spacecraft weight. The costs projected for a similar capacity 18/30 GHz trunking system were approximately $800 for 99.9% rain reliability and about $950 for 99.99% reliability. These are significantly lower than current simplex channel tariffs of $3,500 to $6,500 annually. The bulk of this difference is due to economy-of-scale effect arising from the use of high-capacity millimeter wave satellites. Other operational factors, such as differences in assumed versus actual utilization, would account for the remainder.

For the wideband direct-to-user application, the annual costs were about $200K per user in a 360 terminal 40/50 GHz satellite network. The spacecraft provided 120 half-duplex channels to this network so that on the average each terminal could access the spacecraft 1/3 of the time. However, no site diversity was assumed for this application.

Compensation for rain attenuation aboard the spacecraft led to excessive cost and/or spacecraft weight for configurations having rain reliability in excess of 96%. A similar commercial service would cost approximately $500K/year/terminal; however, it would basically provide 99.99% reliability.

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REFERENCES

1. Millimeter Wave Satellite Concepts, Volume I, Engineering Experiment Station, Georgia Institute of Technology, NASS CR-135227, September 1977.

2. "Business Users Eye 1981 Start Date," Aviation Week and Space Technology, October 17, 1977, pp. 94-95.

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APPENDIX I

ANNUAL COST MODEL FOR A SATELLITE SYSTEM WITH GROUND STATIONS

APPENDIX I

ANNUAL COST MODEL FOR A SATELLITE SYSTEM WITH GROUND STATIONS

Notation

N_S ≡ Life of satellite, years

N_G ≡ Life of ground system, years

H ≡ Length of the financial planning horizon (typically 8 years)

I_S ≡ Present value of the capitalized investment in the satellite system

I_G ≡ Present value of the capitalized investment in the ground system

k ≡ Return on investment (after taxes), i.e., the cost of capital

τ ≡ Marginal income tax rate (typically 48% for corporations and 0% for publically owned systems)

e_{OM} ≡ Annual rate of escalation for operation and maintenance cost (measure of inflation)

Assumptions

1. Annual property taxes are a constant proportion of the total intial investment, and annual fire insurance premiums are constant proportions of the capitalized ground system investment. (Any insurance on the launch should be included in the initial investment in satellite).

2. The capitalized investments are to be fully depreciated over the respective lives of the systems (i.e., ground and satellite).

3. The estimate of operation and maintenance cost for one year is proportional to the capitalized investment.

4. Book value (depreciated value) of assets is roughly equal to their market value. (Any capital gain or loss would be negligible regardless of when assets were sold).

5. The allowable return on investment is that discount rate, which when applied to all costs and revenues, yields a net present value of zero over the planning horizon. Since all above-cost proceeds are paid to investors,

the return on investment is identical to the cost of capital and is therefore the appropriate discount rate for computing present values.

6. The planning horizon in this high technology/high risk-of-obsolescence project is fairly short. In general, the planning horizon is less than the expected equipment lives i.e., $H<N_S$ and $H<N_G$.

7. Period expenses (non-capitalized costs) are to be financed out of current or retained earnings. That is, current expenses are not financed through the issuance of stock or bonds.

Overview of the Relationship Among the Elements of the Model

The earning associated with any investment above the allowable rate of return must be zero in a regulated industry. The authority prescribing the allowable rate of return on investment sets it only as high as necessary to insure the industry's access to the financial markets. This sort of regulation therefore implies that the rate of return on investment is just equal to the cost of capital. The structure of the model follows then from the requirement that the present value of all cash flows over the planning horizon must be zero when discounted at the cost of capital (i.e., money in equals money out). Let t denote the time (year) corresponding to cash flows and let PV {X} = present value of X. Mathematically,

$$PV(X_t) = \sum_{t-1}^{H} \frac{X_t}{(1+k)^t}$$

The basic equation is:

$$PV(\text{Cash inflow}_t) = PV(\text{Cash outflow}_t)$$

where

$$PV(\text{Cash inflow}_t) = PV(\text{Revenue}_t + \text{bond sales}_t + \text{stock sales}_t + \text{after tax disposal value}_H)$$

and

$$PV(\text{Cash Outflow}_t) = I_S + I_G + PV(\text{cash dividends}_t + \text{return of equity principal of stocks}_t + \text{interest paid on bonds}_t + \text{retirement for bonds}_t + \text{income taxes}_t + \text{property taxes}_t + \text{property and fire insurance}_t + \text{operation and maintenance}_t)$$

The stock and bond sales used in the return on investment computations are just equal to the capital investment, i.e., I_S+I_G=PV(Bond Sales + Stock Sales) by assumption #6. Further, the present value of return of equity principal and debt retirement is, by definition, $(I_S+I_G)/(1+k)^H$. Abreviating the notation somewhat, income taxes in each period t are given by the expression:

$$\text{Income tax}_t = \tau[\text{Rev}_t-(\text{Int}_t+\text{Dep}_t+\text{Prop Tax}_t+\text{Insur}_t+\text{O\&M}_t)].$$

Using the previous two observations, income tax_t, bond sales_t, and stock sales_t, can be eliminated from the net cash flow model yielding the simpler form:

$$\text{PV}(\text{Rev}_t) = \frac{1}{1-\tau}[I_S+I_G-\text{PV}(\text{DispVal}_H)]-\frac{\tau}{1-\tau}\text{PV}(\text{Int}_t+\text{Dep}_t)+$$
$$\text{PV}(\text{Prop Tax}_t+\text{Insur}_t+\text{O\&M}_t)$$

By assumption #5, this must just equal the PV (total cost) over the planning horizon. That is: PV (Total Cost) = PV (Rev_t). This PV (Total Cost) can be expressed as an equivalent stream of equal annual costs referred to as the annualized cost, AC.

$$\text{AC}=\text{PV}(\text{Rev}_t)\quad\left[\frac{k}{1-(1+k)^{-H}}\right]$$

This annualized cost figure may be prorated over appropriate system parameters (e.g., number of channels, etc.) to develop any desired measures of average cost/unit of capacity.

<u>Derivation of the Detailed Model</u>

As noted earlier, the appropriate discount rate to be used in analyzing investments in a regulated industry is the cost of capital to the firm. Denoting this after-tax annual rate by k, it can be estimated with the expression:

$$k = (1-\tau)K_dD+K_cC+K_pP$$

where D is the ratio of debt to total capitalization, C is the ratio of common stock to total capitalization of the firm, and P is the ratio of preferred stock to total capitalization. (Note that C+P+D=1). The constants K_d, K_c, and K_p are the costs of debt, common stock capital, and preferred stock capital respectively.

For publicly owned systems there is no equity capital and no income tax. Therefore, the cost of capital is simply K_d. This is only an approximation since the D, C, and P ratios generally vary somewhat over time; similarly the K_d, K_C, and K_p are subject to some external influences and so would not in fact be constant. The relationship given in the expression for k is probably adequate and justified for most purposes. Regardless of the actual mix of instruments used to finance any particular investment, it is standard practice to use a cost of capital corresponding to the firms overall capital structure, i.e., based on D, C, P.

The annual interest on the debt financing is constant; the present value of these period costs is

$$PV(Int_t) = PV(K_d D[I_s+I_G])$$

The conservative convention will be adopted that all time distributed costs are incurred at the beginning of the associated time period.

$$PV(Int_t) = K_d D(I_s+I_G) \sum_{t=o}^{H-1} \left(\frac{1}{1+k}\right)^t$$

Here and in the following expression, closed forms are easily obtained by noting that individual terms comprise geometric series.

$$PV(Int_t) = K_d D(I_s+I_G) \frac{1+k}{k} \left[1-\left(\frac{1}{1+k}\right)^H\right]$$

By assumption #6, the annual depreciation is a constant

$$PV\{DEP_t\}=PV\left[\frac{I_S}{N_s}+\frac{I_G}{N_G}\right]$$

$$PV\{DEP_t\} = \left(\frac{I_S}{N_S}+\frac{I_G}{N_G}\right) \frac{1+k}{k} \left[1-\left(\frac{1}{1+k}\right)^H\right]$$

Using assumption #4, the present value of the disposal value of the investment at the end of the planning horizon, i.e., after period H, is

$$PV(DispVal_H) = \frac{1}{(1+k)^H} \left[I_S\left(1-\frac{H}{N_s}\right) + I_G\left(1-\frac{H}{N_G}\right)\right], \text{ or}$$

$$PV(DispVal_H) = \frac{I_S+I_G}{(1+k)^H} - \frac{H}{(1+k)^H} \left[\frac{I_S}{N_S} + \frac{I_G}{N_G}\right]$$

By assumption #1,

$$PV(Prop\ Tax_t) = PV(K_{TAX}(I_S+I_G)), \text{ or}$$

$$PV(Prop\ Tax_t) = K_{TAX}(I_S+I_G) \frac{1+k}{k} \left[1-\left(\frac{1}{1+k}\right)^H\right]$$

where K_{TAX} is a constant.

Similarly, by assumption #1,

$$PV(Insur_t) = PV(K_{INS}I_G), \text{ or}$$

$$PV(Insur_t) = (K_{INS}I_G) \frac{1+k}{k} \left[1-\left(\frac{1}{1+k}\right)^H\right]$$

where K_{INS} is a constant.

Finally, it is assumed that the first-year operation and maintenance cost is a linear function of the initial investments in both the satellite and ground systems.

$$O\&M_o = K_1 I_S + K_2 I_G.$$

These O&M costs are assumed to increase over time at a rate e_{OM}.

$$PV(O\&M_t) = (K_1 I_S + K_2 I_G) \left(\frac{1+e_{OM}}{k-e_{OM}}\right) \left[1-\left(\frac{1+e_{OM}}{1+k}\right)^H\right], \text{ if } e_{OM} \neq k$$

and

$$PV(O\&M_t) = (K_1 I_S + K_2 I_G)H, \text{ otherwise}.$$

substituting all these relationships into the $PV(Rev_t)$ expression yields:

$$PV(Rev_t) = \frac{1}{1-\tau} \left[(I_S+I_G) - \frac{(I_S+I_G)}{(1+k)^H} + \frac{H}{(1+k)^H}\left(\frac{I_S}{N_S} + \frac{I_G}{N_G}\right)\right] + \left(\frac{1+k}{k}\right)\left[1 - \left(\frac{1}{1+k}\right)^H\right]$$

$$\cdot \{K_{TAX}(I_S+I_G) + K_{INS}I_G - \frac{\tau}{1-\tau}\left[I_S\left(\frac{1}{N_S} + K_d D\right) + I_G\left(\frac{1}{N_G} + K_d D\right)\right]\} + PV(O\&M_t)$$

where $PV(O\&M_t)$ is given explicitly by the conditional expression directly above.

The allowable annual cost, or annual charge, is then calculated from this present value of the allowable revenue stream by

$$\text{Annual Cost} = \frac{k}{1-(1+k)^H} \cdot PV(Rev_t),$$

where H is the length of the planning horizon and k is the allowable return on investment.

APPENDIX II

COMMUNICATION SATELLITE CHANNEL CAPACITY

APPENDIX II

COMMUNICATION SATELLITE CHANNEL CAPACITY

1. Background

The channel capacity of a satellite transponder depends upon a number of inter-related factors. The primary considerations are satellite effective isotropic radiated power (EIRP), transponder linearity, transponder bandwidth, and earth station G/T. With these conditions established, further channel capacity dependence is noted on modulation type, multiplexing system, and the number of accessing carriers.

For the two applications considered in this study, the satellite EIRP and earth station G/T were varied to produce the cost tradeoffs. The transponder bandwidth was fixed at one gigaHertz. The transponder linearity was completely unknown. For calculations, a linearity similar to the Intelsat traveling wave tube (TWT) transponders was assumed. The Intelsat IV transponder capacity as a function of earth station G/T is shown in Figure II-1. This figure shows the capacity for four modulation/multiple access configurations: (1) FDM/FM single carrier; (2) FDM/FM multiple carriers; (3) SPADE (single channel per carrier); and (4) TDM. The reduction in channel capacity as a function of the number of stations accessing a satellite transponder in the FDM and TDM configurations is shown in Figure II-2. The information from these figures is used to estimate the channel capacity of the millimeter wave satellite systems.

2. Application I

The Application I system was based on a few high traffic earth stations. The systems were optimized for FDM and TDM. The channel capacity for the FDM system may be calculated based on the Figure II-1 curve FDM/FM single carriers per transponder curve and the Figure II-2 curve at five stations since the system was based on combining the up-link signals in a single transponder for each downlink. To use these curves, their bases must be taken into account. Figure II-1 is based on a two Watt satellite transmitter with a 19.5 dB gain antenna for an EIRP of 22.5 dBW in a 36 MHz bandwidth which results in an earth station received carrier to noise ratio of about 15 dB. The Application I FDM case was based on a 221 Watt satellite transmitter with a 58 dB gain antenna for an EIRP of 81.4 dBW in a 1 GHz bandwidth which results in an earth station illumination level of -107 dBW/m^2.

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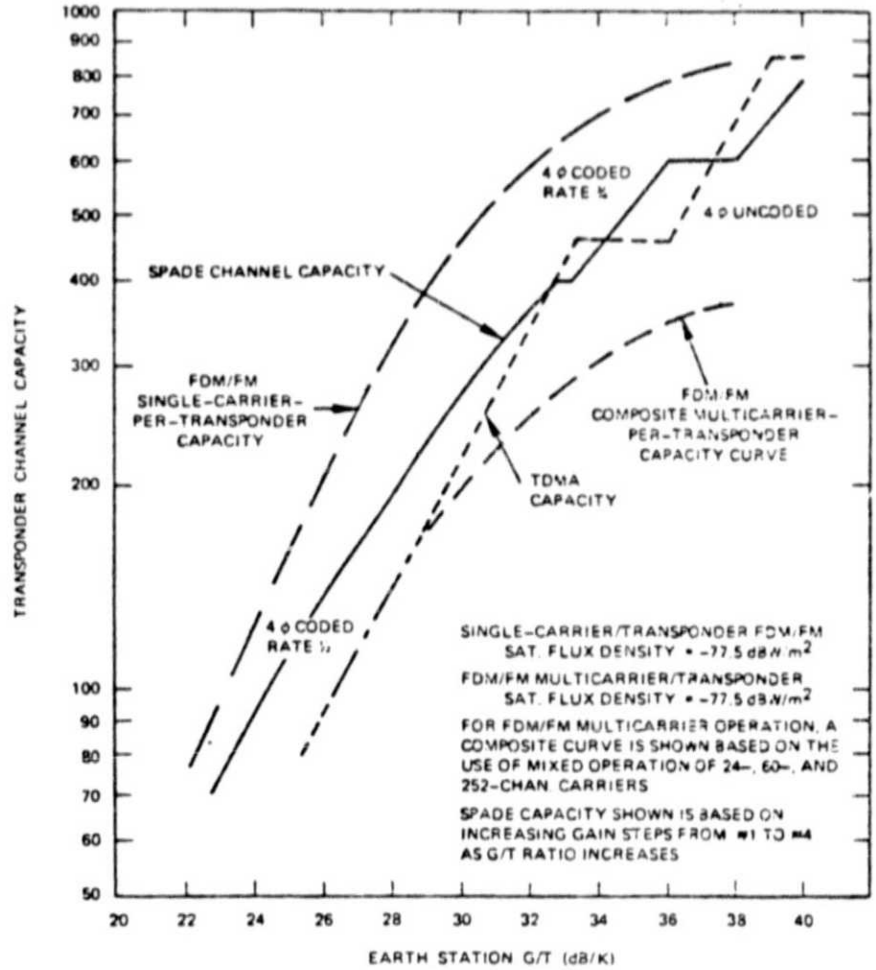

Figure II-1 Global-Beam Transponder Channel Capacity as a Function of Earth Station G/T for Intelsat IV.

Source: COMSAT Technical Review, Volume 4, No. 1, Spring 1974, page 94.

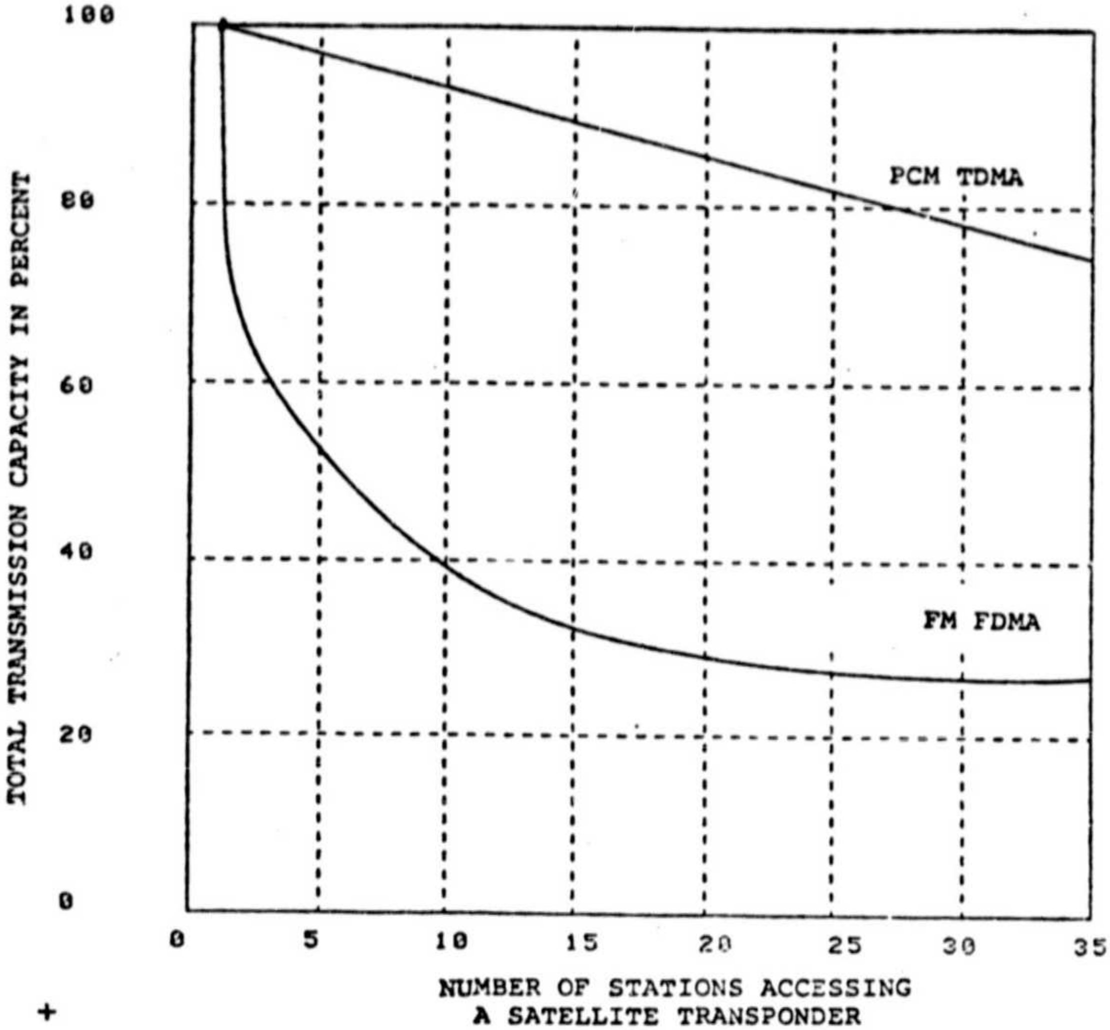

Figure II-2 Transmission Capacity as a Function of the Number of Accessing Earth Stations.

Source: U.S. Department of Commerce "Technical Considerations of Small Fixed, Mobile, and Transportable Satellite Systems," Page 42, NTIS PB266660, March 1977, Office of Telecommunication in Anapolis, Maryland.

By shifting the curve of Figure II-1 by approximately 3 dB/K to the left to account for the increase in power flux density, the difference in frequency bandwidth, precipitation attenuation, and other losses and multiplying the channel capacity by 25 to account for the increased bandwidth available, the curve in Figure II-3 may be derived in this admittedly extremely approximate procedure to yield the Application I transponder capacity versus earth station G/T. With the optimized G/T of 46.5 dB/K for the selected system, it may be seen that the transponder is operating in the bandwidth limited mode with a capacity of about 21,250 times 52 percent (5 carriers accessing each transponder, Figure II-2) or 11,050 simplex voice channels. Therefore, the six transponders will have a capacity of about 66,300 simplex voice channels or 33,150 full duplex voice channels. In a similar manner, the channel capacity for the TDM system may be calculated. The Figure II-3 curve may also be used to determine TDM capacity in conjunction with the TDM portion of Figure II-2. Therefore, the channel capacity for TDM is 21,250 times 97 percent or 20,612 simplex voice channels. The full six transponder capacity would be 123,672 simplex channels or 61,836 full duplex channels. System capacities for various numbers of terminals are given in Table II-1.

3. Application II

Application II provided continental U.S. coverage through switchable spot beams. The basic satellite communications system used FDM with six one gigaHertz bandwidth transponders. The satellite transmitter power out is 28.3 Watts with a 51.6 dB gain antenna for an EIRP of 66.1 dBW in a one GHz bandwidth for a received flux density of -108.3 dBW/m^2. With an earth station G/T of 32.1 dB/K, the system is power limited with a capacity of 16,350 times 52 percent or 8,500 simplex channels per transponder. Thus, the total satellite capacity is 51,000 simplex or 25,500 full duplex voice channels or nine one-way video channels per transponder for a total of 54 video channels. The capacity for television signals will be nine one-way video channels per transponder for a total satellite capacity of 54 channels.

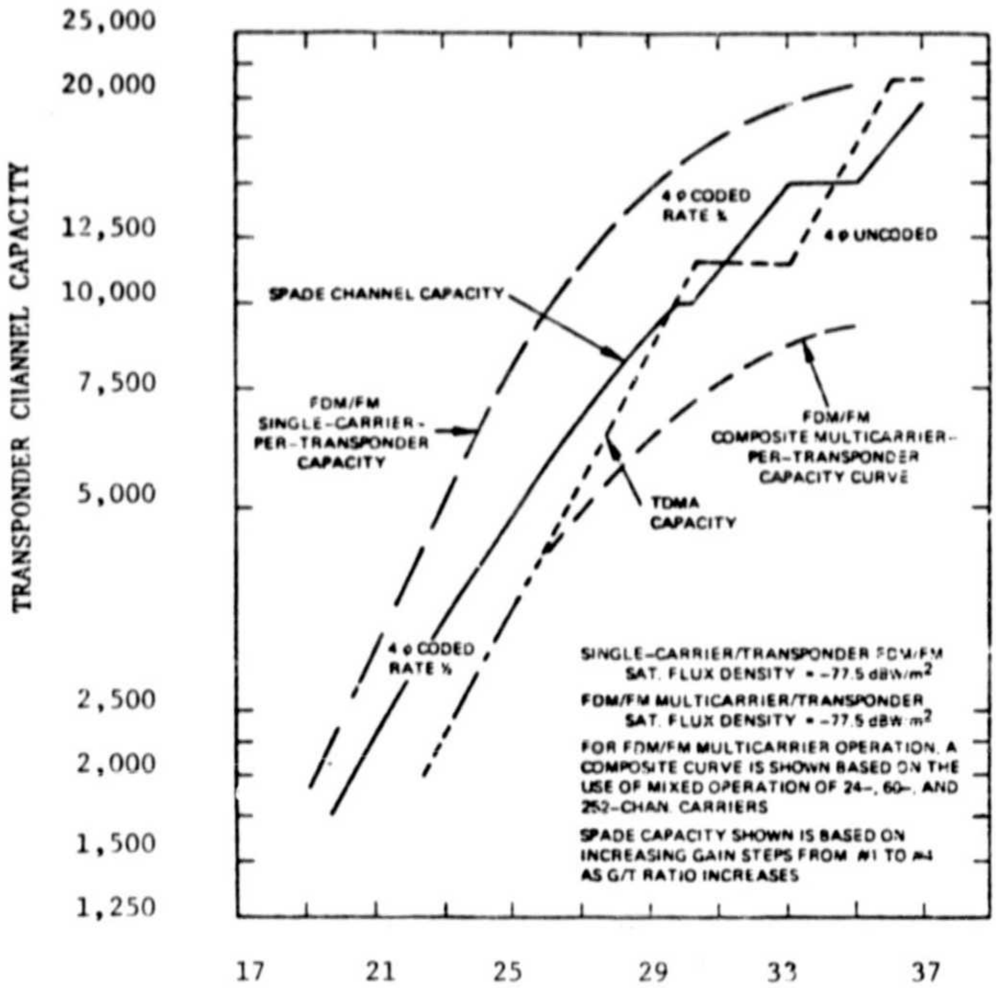

Figure II-3 Global-Beam Transponder Channel Capacity as a Function of Earth Station G/T for Millimeter Wave Satellite Study.

TABLE II-1

System Channel Capacity as a Function of the Number of Earth Terminals

		FDM			TDM		
Number of Terminals In System	Number of Terminals Accessing Each Transponder	% Transmission Capacity from Figure II-2	Number of Simplex Voice Channels Per Transponder	Total Number of Simplex Voice Channels (100% Utilization)	% Transmission Capacity from Figure II-2	Number of Simplex Voice Channels Per Transponder	Total Number of Simplex Voice Channels (100% Utilization)
2	1	100	21,250	42,500	100	21,250	42,500
4	3	61	12,962	51,848	98.5	20,931	83,724
6	5	52	11,050	66,300	97	20,612	123,672
8	7	48	10,200	81,600	95.5	20,293	162,344
10	9	41	8,712	87,120	94	19,975	199,750